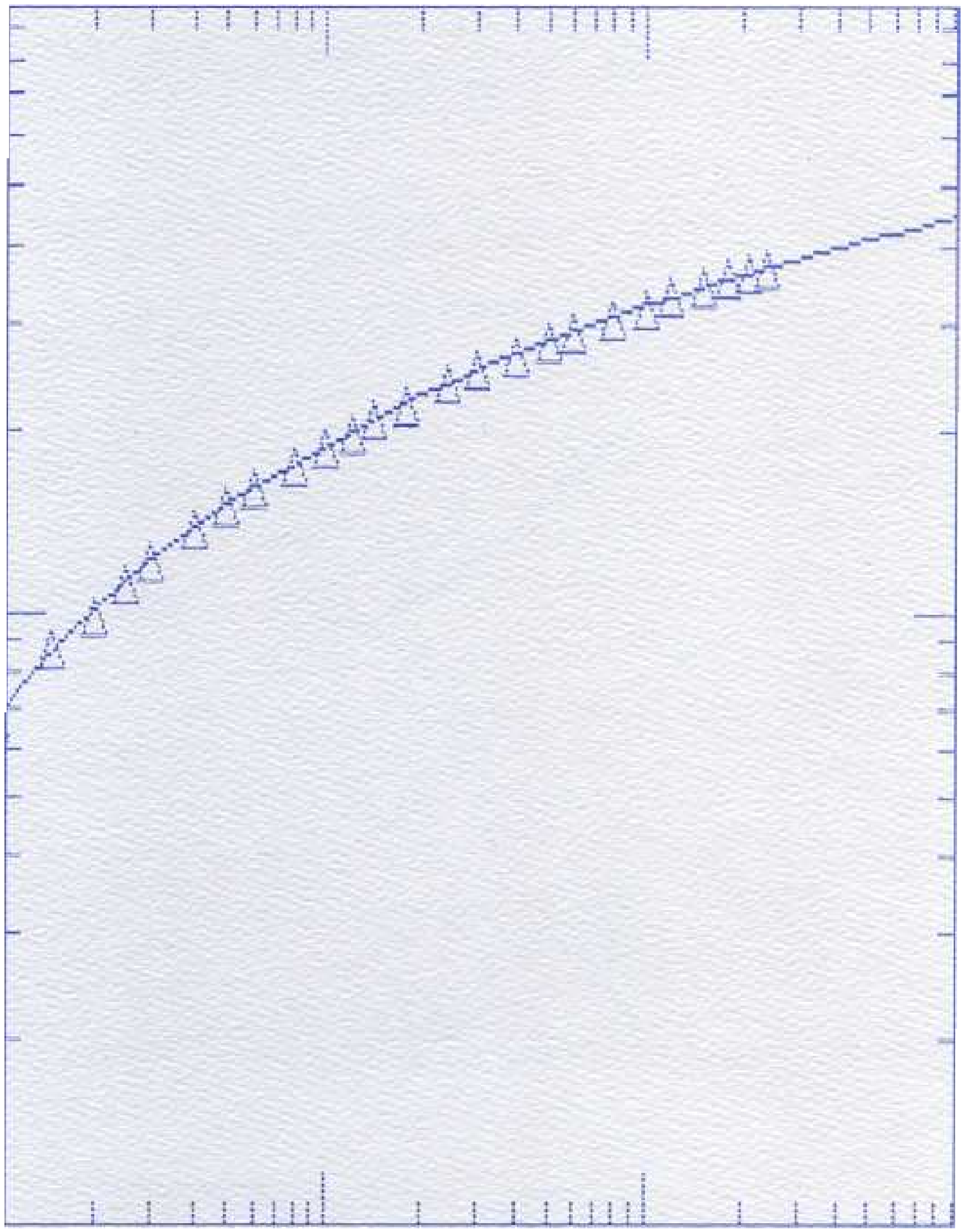
Aquifer Testing for Hydrogeologic Characterization

Guidance Manual for Ground Water Investigations



State of California
Environmental Protection Agency

AQUIFER TESTING FOR HYDROGEOLOGIC CHARACTERIZATION

Guidance Manual for Ground Water Investigations

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The California Environmental Protection Agency:

Department of Toxic Substances Control
State Water Resources Control Board
Integrated Waste Management Board
Air Resources Board
Department of Pesticide Regulation
Office of Environmental Health Hazard Assessment

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FOREWORD

The California Environmental Protection Agency (Cal/EPA) is charged with the responsibility of protecting the state's environment. Within Cal/EPA, the Department of Toxic Substances Control (DTSC) has the responsibility of managing the state's hazardous waste program to protect public health and the environment. The State Water Resources Control Board and the nine Regional Water Quality Control Boards (RWQCBs), also part of Cal/EPA, have the responsibility for coordination and control of water quality, including the protection of the beneficial uses of the waters of the state. Therefore, the RWQCBs work closely with DTSC in protecting the environment.

To aid in characterizing and remediating hazardous substance release sites, DTSC had established a technical guidance work group to oversee the development of guidance documents and recommended procedures for use by its staff, local governmental agencies, responsible parties and their contractors. The Geologic Services Unit (GSU) within DTSC provides geologic assistance, training and guidance. This document was prepared by GSU staff in cooperation with the technical guidance work group and the RWQCBs. This document provides guidelines for the investigation, monitoring and remediation of hazardous substance release sites. It should be used in conjunction with the two-volume companion reference for hydrogeologic characterization activities:

Guidelines for Hydrogeologic Characterization of Hazardous Substances Release Sites
Volume I: Field Investigation Manual
Volume 2: Project Management Manual

Please note that, within the document, the more commonly used terms, ***hazardous waste site*** and ***toxic waste site,*** are used synonymously with the term hazardous substance release site. However, it should be noted that any unauthorized release of a substance, hazardous or not, that degrades or threatens to degrade water quality may require corrective action to protect its beneficial use.

This document supersedes the 1990 draft of the DTSC, *Scientific and Technical Standards for Hazardous Waste Sites*, Volume I, Chapter 11, and is one in a series of Cal/EPA guidance documents pertaining to the remediation of hazardous substance release sites.

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Finally, thanks are extended to the staff of the Geological Support Unit and to the many anonymous reviewers outside DTSC, whose comments were indispensable for completing this document.

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INTRODUCTION

Purpose

This document provides guidelines for the application of aquifer pumping and slug tests in the characterization of hazardous waste sites. The purpose of this document is to aid in the design and performance of aquifer tests, provide recommended quality assurance and quality control (QA/QC) procedures, and present a standardized approach to the presentation of the resulting data.

The recommendations presented here are a subset of the larger hydrogeologic characterization process. The additional investigative tools necessary to adequately characterize a site, as well as recommendations for their use, are outlined in Guidelines for Hydrogeologic Characterization of Hazardous Release Sites (Cal/EPA, 1995).

1.2 Application

Aquifer pumping and slug tests are useful for providing information on aquifer properties that influence contaminant transport. These parameters provide important information for selecting and designing ground water cleanup remedies, and are used as input to mathematical calculations or computer models that are used to analyze ground water flow and contaminant movement.

These guidelines are intentionally not site specific, exhaustive, or detailed specifications for each type of disposal or cleanup situation that may occur. Instead, these guidelines are meant to provide investigators and responsible parties with information needed to reduce regulatory uncertainties associated with cleaning up a hazardous substance release site.

Limitations

The recommendations presented here represent minimum criteria to aid in obtaining quality data and assuring reasonable and independently verifiable interpretations. Some sites may require investigative efforts above and beyond the scope of this document, while at other sites a less rigorous application of this guidance may be appropriate. It is the obligation of the responsible parties and the qualified professionals performing site investigations to consult with pertinent regulatory agencies, identify all requirements and meet them appropriately.

This document contains guidelines for conducting and interpreting aquifer tests at hazardous substance release sites in California. It does not define specific operating procedures for conducting aquifer tests or for interpreting the results. The qualified professional in charge of the field investigation should specify methods, instruments and operating procedures in an appropriate work plan and document any significant departures from the work plan that were necessary during the course of the investigation.

This document does not supersede existing statutes and regulations. Federal, state and local regulations, statutes, and ordinances should be identified when required by law, and site characterization activities should be performed in accordance with the most stringent of these requirements where applicable, relevant and appropriate.

2 AQUIFER TESTS - GENERAL CONSIDERATIONS

Pumping tests and slug tests provide a means of determining hydraulic properties of water-bearing and confining zones in the subsurface. Appropriately planned and conducted tests help define the overall hydrogeologic regime of hazardous waste sites and regional ground water flow systems.

2.1 Guidelines for Preliminary Aquifer Test

Corrective actions or remedial measures at hazardous waste sites depend on adequate characterization of the hydraulic properties of geologic material at the sites. While aquifer tests can aid in this Characterization, the number of tests to be performed, the locations of these tests, and the overall test set-up depend on (1) a clear definition of the problem, (2) the amount of information desired, and (3) the availability of funds (Kruseman and de Ridder, 1983). The last three items can be determined only if preliminary site characterization work has been conducted properly. Therefore certain preliminary steps should be taken to assure the reliability of time, drawdown, and discharge measurements (Driscoll, 1986), and to allow for the incorporation of aquifer test results into the site characterization process.

2.1.1 Establishment of Geologic Conditions

Because geologic conditions govern the hydrogeologic regime, geologic conditions should be investigated and recorded before an aquifer test is conducted. This knowledge should be used in conjunction with preliminary knowledge of hydrogeologic conditions at the site to establish the proper logistical configuration of the aquifer test. The following basic geologic data should be collected, reviewed and/or interpreted prior to the initiation of an aquifer test:

- surface geology (including soil investigation(s)) of the site and nearby areas, both locally and regionally,
- lithologic composition of the aquifer(s) and confining bed(s) of interest,
- lateral and/or vertical compositional changes of the aquifer(s) and confining bed(s) of interest, and
- thickness of the aquifer(s) and confining bed(s)of interest.

2.1.2 Establishment of Hydrogeologic Conditions

Aquifer tests can improve characterization of ground water flow and contaminant transport at hazardous waste sites. However, the following preliminary hydrogeologic data should be established, by either assessing existing data or collecting new data, prior to the initiation of an aquifer test:

- existence and nature of aquifer boundaries,
- direction of ground water flow in the aquifer(s) of interest,

- determination of the magnitude and direction of horizontal and vertical hydraulic gradients,

- existence of seasonal ground water fluctuations or any regional water level trends or ground water use operations that may influence the aquifer(s) and confining bed(s) of interest, and

- approximate estimates of the hydraulic properties for the zones of interest.

All preliminary hydrogeologic conditions should be investigated and recorded before an aquifer test is conducted, and should be used in conjunction with knowledge of basic geologic conditions at the site to establish the proper configuration and logistics of the aquifer test.

3 DESIGN OF AQUIFER PUMPING TESTS

The mechanics of aquifer pumping tests are such that water is pumped (a) from a well screened in a particular water-bearing zone, (b) for a certain amount of time, and (c) at a specific pumping rate. For this reason, these tests are often referred to as **pumping tests** The impact of ground water extraction on one or more water level surfaces (i.e., the water table and/or piezometric levels of confiied or semi-confiied zones), or drawdown, is measured in the pumped well and in other nearby wells, referred to as observation wells. Subsequently, the hydraulic properties of the aquifer--specifically transmissivity, hydraulic conductivity, and storage coefficients--can be estimated from the drawdown observations.

3.1 Establishment of the Configuration and Logistics of the Aquifer Test

Aquifer test site selection and overall set-up directly affect the quality of data obtained during the test and the reliability of data analysis results. Establishment of the configuration and logistics of the aquifer test should therefore combine the practical restrictions of the test site with constraints imposed by assumptions inherent in the mathematical equations used for aquifer test data analysis. As a minimum, the following considerations should be incorporated into the aquifer test design:

- hydrogeologic conditions of the aquifer test area should be fairly continuous and should be representative of the hazardous waste site or area of interest,

- the test site should preferably not be affected by nearby pumping, railroads, highways, or other areas or conditions that could produce irregular water level fluctuations in wells,

- the hydraulic gradient of the water table or piezometric surface should be small,

- the barometric efficiency of the aquifer should be determined and described (its response to changing atmospheric pressure),

- pumped water should be prevented from recharging the zone(s) being pumped, and

- appropriate personnel and equipment should be accessible to the test site.

The aquifer test configuration and the rationale for establishing the particular configuration and logistics for an aquifer test should be included in the appropriate site investigation report. The report should include documentation of the aquifer test, a presentation of the test data, and the aquifer test results. In the event that the actual test is modified from the original Configuration and/or logistics, the actual aquifer test configuration and logistics should be adequately explained and a rationale for any deviation from the original design should be presented in the site investigation report. The aquifer test configuration should include, but not be limited to the following:

- identification of the zone to be pumped,
- identification of known or suspected aquifer boundaries,
- identification of all zones (or depths, if applicable) monitored by observation wells during the aquifer test, and
- identification of the areal distribution of all observation wells monitored during the test.

3.2 Guidelines for the Pumping Well

Specifics related to the design and construction of pumping wells can be found in Driscoll (1986). However, the following guidelines represent minimum considerations that should be adhered to for wells used as pumping wells during an aquifer test.

3.2.1 Well Diameter

The casing diameter of the pumping well should accommodate an appropriately sized pump with adequate clearance for installation and hydraulically efficient operation.

3.2.2 Well Depth

The total depth of the pumping well should be selected based on lithologic information obtained from the following sources:

- geologic cross-sections,
- geologic logs, and
- geophysical logs.

This information should be obtained from the installation of a smalldiameter pilot hole, applicable records of nearby wells, and/or from drilling and installation of the pumping well itself. Data used to select the total depth of the pumping well should be included in the site investigation report.

3.2.3 Well Screen Length

The length of the screened interval of the pumping well directly influences both the flow of water to the well and the amount of water that can be extracted by the well. Each of these aspects is important with respect to hazardous waste sites. Ideally, for the purposes of aquifer testing it is desirable to screen the entire thickness of the zone of interest. However, if 70 to 80 per cent of the aquifer thickness is screened, approximately 90 per cent or more of the well's maximum yield can be obtained, and the well can therefore be assumed to approximate fully penetrating conditions (Kruseman and de Ridder, 1983). In addition to optimizing yield, fully penetrating conditions allow for horizontal ground water flow towards the pumping well, which is one of the assumptions upon which many aquifer test analysis methods are based. If it is not practical to screen even 70 to 80 per cent of the zone of interest due to natural (such as aquifer type, configuration, or heterogeneity) or economic constraints, then ground water will be induced to flow towards the well with both horizontal and vertical components. Such situations will artificially increase the magnitude of drawdown and may lead to misinterpretation of the aquifer's hydraulic properties. In these instances, analysis should account for partial penetration so that the actual effect of pumping on the zone(s) of interest can be determined (Kruseman and de Ridder, 1983 and Freeze and Cherry, 1979). Justification for the partial penetration and a detailed description of the proposed or actual analysis should be included in the site investigation report.

3.2.4 Determination of Screen Slot and Filter Pack Size

In addition to allowing water to enter the pumping well, another use of the well screen is to retain aquifer material that would otherwise enter the pumping well. Both the screen slot size and the filter pack material gradation should be designed on the basis of the grain size distribution of the aquifer material, and should allow for adequate development of the pumping well. Refer to Monitoring Well Design and Construction for Hydrogeologic Characterization (Cal EPA, 1995) for more information on well design. The ultimate hydraulic efficiency of the pumping well is influenced by its design and construction. The rationale for design should be included in the site investigation report, and should be accompanied by appropriately labeled "as-built" drawings of the pumping well.

3.2.5 Selection of the Pumping Rate

The maximum practical pumping rate is typically determined by conducting a step-drawdown test before the constant-rate aquifer test begins. Several references are available for detailed examinations of the mechanics of step-drawdown tests (for example, Driscoll, 1986, Kruseman and de Ridder, 1983) and how they can be used to determine the optimum pumping rate for an aquifer test, to calculate well operating levels for different long-term pumping rates, and to indicate the efficiency of the well. The following are the minimum requirements that should be followed to ensure that an acceptable pumping rate is selected for the aquifer test.

- A step-drawdown test, using at least three successively greater pumping rates, should be performed before commencement of the constant rate aquifer test in order to establish an optimum pumping rate for testing hydraulic properties of the aquifer (and confining beds, where applicable) of interest.

- The duration of pumping for the step-drawdown test should be the same for each pumping rate (one to two hours).

- The selection of pumping rates should be based on the pumping rate of nearby wells established in the zone(s) of interest, or on reliable and substantiated estimates of pumping rates based on the geologic composition of the zone to be pumped. A rationale for the selection of the pumping rates should be included in the site investigation report.

- Drawdown measurements should be plotted versus time for all pumping episodes on the same data plot and should be presented in the site investigation report. A detailed discussion explaining how the data support selection of an appropriate pumping rate should be included in the site investigation report.

- Before the constant-rate aquifer test begins, sufficient time should be allowed for water levels to return to static conditions. The amount of time necessary for recovery of water levels should be documented in the site investigation report.

3.2.6 Pump Selection

As a minimum, the following guidelines should be incorporated into the pump selection process prior to initiation of the aquifer test.

- The pump and power supply should be capable of operating continuously at an appropriate constant discharge rate for at least the expected duration of the aquifer test.

- The capacity of the pump should be sufficient to allow the pump to operate at the rate determined in the step-drawdown test.

3.2.7 Discharge and Disposal of Pumped Water

Quantifying the hydraulic properties of an aquifer (or confining bed) requires that water be withdrawn from a known zone for some period of time, during which the extracted water cannot re-enter the zone being pumped. To prevent the discharge water from recharging the zone being pumped, appropriate conveyances and/or pathways from the discharge line to an appropriate point of disposal or containment should be established. Driscoll(1986) and Kruseman and de Ridder (1983) describe various means and devices for the discharge of pumped water.

Because many aquifer tests are conducted to address ground water quality problems, the proper discharge of water extracted during these tests may require more stringent control than does discharge related to water supply issues. Therefore, at hazardous waste sites, water extracted during aquifer tests may have to be contained, sampled to assess the presence of contaminants, and if necessary, treated or disposed of at an appropriate permitted facility. Before the aquifer test begins, the volume of water expected to be extracted during the test should be predicted based on a reasonable estimate of the pumping rate and duration of the test. This volume should then be used to determine the appropriate number and size of leak-proof containers that should be used to contain the discharged water. In order to establish the existence or absence of contamination in the discharged water, the water should be sampled from each container and analyzed in a manner that is appropriate for the type(s) of contamination that are suspected or known to exist at the hazardous waste site. Discharged water must be treated or disposed of in accordance with applicable laws and regulations. In most instances, such discharges will be required to conform to limitations specified in the California Code of Regulations, Title 23; consultation with Regional Water Quality Control Board staff regarding treatment and disposal options is recommended.

3.3 Guidelines for Observation Wells

Provided that an aquifer test has been appropriately designed to stress the aquifer or zones of interest, drawdown measurements can be taken from both the pumping well and properly placed observation wells. However, data obtained from the pumping well is typically less desirable for calculations of hydraulic properties because of irregularities induced by the operation of the pump (Driscoll, 1986), and due to the effects of well inefficiency and well bore storage. Obtaining drawdown data from an observation well (or wells) allows for the assessment of the pumped zone's hydraulic properties over a larger area. Collaborative data from more than a single location allow for more reliable determinations of transmissivity, hydraulic conductivity, and the storage coefficient.

Prior to initiation of an aquifer test, the main concerns regarding observation wells are the number to be used throughout the test, their distance and orientation with respect to the pumping well, and how they are constructed. As a minimum, the technical guidelines listed below should be implemented to ensure that these concerns are appropriately addressed.

3.3.1 Number of Observation Wells

The appropriate number of observation wells is dictated by the complexity of the geology and hydrology at the hazardous waste site and the amount and accuracy of information desired. Ideally, at least three observation wells that monitor only the pumped zone should be measured for drawdown throughout the duration of the aquifer test (including the recovery period). Additional wells may be placed to monitor the effect of pumping in surrounding zones (i.e., unpumped aquifers and/or aquitards). Drawdown obtained from a single observation well (not to be confused with a single-well aquifer test) may permit calculation of the test intervals average transmissivity, hydraulic conductivity, and storage coefficient. If two or more observation wells are available for drawdown measurements, data can be analyzed by examining both drawdown versus time and drawdown versus distance relationships. Using both these analytical methods and observing how wells in various locations respond to pumping provide greater assurance that (a) the calculated hydraulic properties are representative of the zone being pumped over a large area, and (b) any heterogeneities that may enhance or restrict the movement of ground water and contaminants have been identified.

3.3.2 Distance of the Observation Wells from the Pumping Well

A rationale explaining the observation well locations should be included in the site investigation report. There are advantages and disadvantages to placing them both near and far from the pumping well. At a minimum, the following parameters should be considered before this distance determination is made for the placement of observation wells in the zone being pumped:

- type and thickness of the aquifer being pumped,
- estimated tranmissivity and storage coefficient of the zone being pumped,
- discharge rate employed throughout the aquifer test,
- screen length of the observation well (which is related to considerations of partial penetration of the pumping well),
- vertical and lateral heterogeneity, and
- anisotropy.

In the event that anisotropy is suspected, observation wells should be located so as to identify directions of potentially enhanced or restricted ground water and contaminant flow. A discussion addressing the placement of observation wells with respect to the pumping well and anisotropic characteristics should be included in the site investigation report.

3.3.3 Design and Construction of the Observation Wells

Observation wells provide a means of monitoring the subsurface to see how it responds to the impact of pumping. If these wells have not been properly designed and constructed, no number of observation wells, no matter where they are located with respect to the pumping well, will yield reliable indications of the hydraulic properties of the zone(s) of interest. As with the pumping well, the following guidelines represent minimum considerations that should be adhered to for wells used as observation wells during an aquifer test.

<u>Observation Well Diameter</u>

The diameter of observation wells should be large enough to accommodate the water level monitoring devices that are expected to be used throughout the aquifer test. The diameter should not be so large as to induce time lags in drawdown changes, nor so small as to allow the water level monitoring devices to lodge in the well.

Length and Location of the Well Screen

Observation wells are typically constructed with screens that are three to ten feet in length. While relatively short screen lengths (three to five feet) are most desirable, longer screens may be advantageous in situations where the pumped zone is composed of stratified material (Driscoll, 1986 and Kruseman and de Ridder, 1983). In such cases, it may be desirable to observe a composite effect due to pumping, and thus calculate average hydraulic properties for the pumped zone rather than discern different properties for each individual layer or lens.

For observation wells that are monitoring the same zone that is being pumped, screens should be installed at approximately the same depth as the central portion of the screen used in the pumping well (Driscoll, 1986). This construction feature (if properly designed) should allow for a rapid water level response in the observation wells that corresponds to water level decline at the pumping well.

It is sometimes desirable to observe the effect of pumping on zones other than that being pumped, to assess any hydraulic connection (leakage) between various geologic materials. By installing observation wells that are properly screened and sealed in the zones surrounding that being pumped, it may be possible to discern both the influence of pumping on these zones and the time at which the surrounding zones begin to influence or be influenced by the pumped zone via leakage. Depending on the degree of hydraulic connection, the response of these observation wells to pumping may be significantly delayed and drawdown may be lessened in magnitude as compared with observation wells monitoring the pumped zone (Driscoll, 1986). Included in the site investigation report should be a discussion addressing the zone or zones monitored by each observation well used during an aquifer test. The discussion should be accompanied by a justification of the length and location of screens used. The justification should include geologic cross-sections, lithologic logs, and as-built drawings of the observation wells. The site investigation report should also contain a map indicating the locations of observation wells with respect to the pumping well, and a table including, at a minimum, each observation well's total depth, screened interval, and distance from the pumping well.

Observation wells should be constructed to allow for the accurate monitoring of change in water levels due to pumping. In order to facilitate this monitoring, observation wells should be constructed with an appropriate filter pack, screen slot size, and annular seal, and should be properly developed (Cal EPA, 1984). The rationale for the selection of filter pack material and screen slot size, annular seal placement, and development technique used for the observation wells monitored during the aquifer test should be included in the site investigation report.

4 PERFORMANCE OF AQUIFER PUMPING TESTS

Water level and discharge (or pumping) rate measurements should be collected throughout the aquifer test.

4.1 Guidelines for Water Level Measurements

Data obtained from the pumping phase of an aquifer test is, of course, important. However, a complete aquifer test also requires considerations of conditions that exist both before and after the pumping phase.

4.1.1 Water Level Measurements Before Initiaion of the Aquifer Test

The pumping phase of an aquifer test should not be started until existing trends in water level changes in the zone(s) of interest have been established (Kruseman and de Ridder, 1983). Two existing trends which should be examined before pumping begins are the water levels for all zones monitored and the effects of barometric pressure. This initial portion of the aquifer test should be incorporated into the overall site characterization process because nearby surface water and ground water level fluctuations may affect the lateral and vertical movement of ground water and certain contaminants at hazardous waste sites. The pumping phase of the aquifer test should begin only if any identified and recorded water level trends are expected to remain relatively constant. A discussion addressing the nature and frequency of any water level trends should be included in the site investigation report. For sites that impacted by tidally influenced water bodies, a representative cycle of the tidal variations should be recorded for the water body itself and for the zone(s) of interest that are affected by the tidal influence. These data should be presented in both tabular form and on data plots (as elevation versus time) in the site investigation report. By identifying such fluctuations, long-term regional trends and short-term variations of water levels can be recognized and removed from the data if their impacts are significant during the pumping phase of the aquifer test. In order to identify these fluctuations, the guidelines below should be followed.

- For at least two days prior to initiation of the pumping phase of the aquifer test, water levels should be measured and recorded on an hourly basis for all zones anticipated to be monitored during the aquifer test. These data should be presented in both tabular form and on data plots (as elevation versus time) in the site investigation report.

- For at least two days prior to the initiation of, and during, the pumping phase of the aquifer test, barometric pressure should be monitored and recorded at least hourly, and compared with water levels monitored for all zones of interest. All data should be presented on data plots at the same scale as the water level data, and should be accompanied by a discussion in the site investigation report describing the effects of each parameter on water levels.

4.1.2 Water Level Measurements During the Aquifer Test

Water level measurements should be taken many times during the course of an aquifer test. Both water level and time should be measured and recorded as accurately as practicable. Copies of all field data sheets or transducer records should be provided in the site investigation report. Therefore, in addition to selecting accurate water level devices, all watches or clocks used for timing the measurements should be synchronized so that each measurement can be referenced to the exact time pumping started (Driscoll, 1986).

Because water levels change rapidly during the early portions of aquifer tests, water level measurements should initially be taken at brief intervals, with the time between measurements gradually increasing as pumping continues. Many references (for example, Driscoll, 1986 and Kruseman and de Ridder, 1983) contain suggested practical time intervals for measuring drawdown in both the pumping and observation wells. Although the actual measuring intervals should depend on local conditions, and on available personnel and/or measuring devices, frequent readings during the first few hours of pumping are necessary for the data analysis phase and the characterization of the hydrogeology at the site.

Water level measurements taken during the aquifer test should be presented in the site investigation report. The format for this presentation should include at least the following information with respect to water level measurements:

- date and time the aquifer test began,
- initial and final water levels for the pumping phase,
- time since pumping started (in minutes),
- measured depth to water,
- drawdown, and
- comments noting any "unusual" events (such as stopping of the pump or changes in discharge rate, changing weather patterns, or passage of a train or heavy machinery).

Because measuring depth to water during aquifer tests at hazardous waste sites are labor intensive and potentially risky with respect to health and safety considerations, the use of electronic depth indicators and recorders (transducers and data loggers) has replaced other manual or mechanical devices for the measurement of water level changes. However, it is often advantageous to confirm electronically obtained drawdown values with periodic manual measurements (see Driscoll (1986) for a discussion of various manual water level measuring devices). It may also be advantageous to install a mechanical continuous water level recorder at the most distant observation well beyond which no impact due to pumping is expected. Mechanical continuous water level recorders can be used to establish long-term trends and short-term variations in water levels before and during the pumping phase of the aquifer test.

All water level measuring devices should be noted in the site investigation report. Whenever more than one water level measuring device has been employed to measure water levels in the same observation well, all devices should be appropriately labeled and indicated on the data plots included in the report. In the event that various devices yield different water level values for simultaneous measurements in the same well, a discussion addressing the discrepancy should be provided in the report. Whenever transducers are used to monitor water levels, a discussion should be provided in the site investigation report indicating that transducers capable of measuring appropriate pressure ranges (when converted to feet or meters of water) have been employed. Transducers should be calibrated to a direct, manual method of measuring water levels both before the aquifer test begins and after the recovery phase of the test. The site investigation report should contain a description of both calibration efforts.

4.1.3 Water Level Measurements During the Recovery Phase of the Aquifer Test

After the pumping phase of the aquifer test is completed, water levels in the pumped well and observation wells will begin to rise; this is the recovery phase of the aquifer test. During this phase, residual drawdown can be measured in the wells. Water levels should be monitored during the recovery phase of the aquifer test with the same frequency used during the pumping phase. Water level measurements taken during the recovery phase should be presented in the site investigation report. As a minimum, the following information should be provided in tabular form:

- date and time the pumping phase ended and the recovery phase began,
- initial and final water levels for the recovery phase,
- time since pumping stopped (in minutes),
- measured water level,
- residual drawdown, and
- records of any noteworthy occurrences.

Calculation of hydraulic properties based on the analysis of recovery data should be used in conjunction with calculations obtained from the pumping phase of the test in order to estimate the true hydraulic properties of the zone(s) of interest. Recovery data are often more reliable than data from the pumping phase because they are not impacted by irregular fluctuations in the pumping rate. As with the early portions of the pumping phase in which water levels drop rapidly, water levels rise rapidly during early portions of the recovery phase and are followed by a decreasing rate of water level rise. It is therefore important to establish the same schedule for obtaining water level measurements during the initial portions of the recovery phase as that used during the pumping phase (Kruseman and de Ridder, 1983).

4.2 Guidelines for Discharge Rate Measurements

Variations in the discharge rate are a major cause of erratic drawdown data (Driscoll, 1986). To ensure that a complete, meaningful set of drawdown data can be obtained once an aquifer test begins, it is important to have (1) an appropriately sized pump with an adequate power supply, (2) a mechanism for controlling discharge, (3) on-site personnel who are sufficiently familiar with pumping equipment to be able to maintain the constant discharge rate determined by the step-discharge test, and (4) a means of obtaining and recording accurate periodic measurements of the discharge rate. It is beyond the scope of these technical guidelines to address pump selection or technical training; however, methods for determining discharge rate are discussed below.

Many references discussing various means of measuring discharge rates are available (see, for example, Driscoll, 1986 and Kruseman and de Ridder, 1983). Whatever method is used, it should be kept in mind that the total expense incurred during an aquifer pumping test is justified by the reliability of the data; if the behavior of the data can only be attributed to mechanical or human error (or lack of planning), then calculation of hydraulic parameters is not possible. The discharge rate should be measured at least once every hour during the aquifer test, with more frequent measurements occurring during the first six hours. The necessary adjustments should be made to keep the discharge rate constant. Discharge rate measurements, the times the measurements were taken, and any appropriate comments with respect to the discharge rate that were compiled during the aquifer test should be presented with the water level data and included in the site investigation report. The means of obtaining discharge rate measurements throughout the aquifer test should also be described in the site investigation report.

4.3 Consideration of Additional Influences

Drawdown values measured during an aquifer test may be influenced by external factors (i.e., influences independent of the activities connected with the aquifer test) for which no allowance is made in the data analysis methods. In addition to tidal influences, examples of these external influences are natural recharge to or discharge from the zone(s) of interest, changes in barometric pressure, evapotranspiration, earth tides, pumping from wells in the general area, and unique water level fluctuations caused by heavy traffic, an earthquake, or sudden, heavy precipitation. If properly monitored, the influence of some of these external factors can be removed from water level data because of their regular, sometimes cyclical patterns; other influences may render the aquifer test data useless. Because an aquifer test is conducted to determine the hydraulic properties of a zone (or zones) that is solely impacted by the force of pumping, the following guidelines should be adhered to in order to assess the impact of additional external factors on the data obtained during an aquifer test.

- A barometer and/or a barograph should be used to monitor barometric pressure during the aquifer test. Data obtained from this equipment should be presented in the report at the same scale as the drawdown data.

- In the event that any water level data obtained during the aquifer test may have been subjected to external influences, the site investigation report should contain a discussion addressing the consequent impact on hydraulic parameter calculations and, if applicable, a rationale for removing the influence(s) from the drawdown data.

The nature and time of any weather changes should be recorded in the field and should be discussed in the site investigation report.

4.4 Establishing the Duration of the Aquifer Test

Ideally, aquifer tests should be continued until equilibrium (steady state) is reached and no further drawdown occurs (i.e., until the cone of depression stabilizes because the amount of recharge into the aquifer equals the pumping rate). In practice, equilibrium is rarely attained, and the length of the aquifer test ultimately should depend on the hydraulic properties of the zone(s) of interest. The only fact that can be deduced with any certainty is that because the cone of depression expands more slowly in an unconfined aquifer than in a confined aquifer of equal transmissivity, it takes unconfined aquifers longer to reach steady state. In addition, unconfined aquifers may exhibit delayed yield from drainage of pore spaces. Therefore, aquifer tests conducted in unconfined aquifers should be run longer than confined aquifer tests. The actual length of the aquifer test necessary to define the hydraulic properties of specific zones at a particular hazardous waste site depends on the regional and local geological and hydrological setting. Under no circumstances should an aquifer test be terminated prematurely, because the resulting limited data set may not indicate the true nature of the zone(s)of interest (Driscoll, 1986).

It is advisable to manually plot drawdown data during the aquifer test. Preliminary plotting will often display anomalies in the data, may indicate how much longer the test should continue, and may reveal the presence of suspected or previously unknown boundaries.

The determination of the length of an aquifer test should be based on at least the following considerations:

- geologic composition of the zone(s) of interest,
- hydrogeologic nature of the zone(s) of interest (i.e. confined, unconfined),
- existence of suspected or known boundaries and their impact on the movement of ground water and contaminants at the test site, and
- other aquifer tests performed nearby in the same aquifer zone.

A rationale explaining how the length of the aquifer test was established should be provided in the site investigation report.

4.5 Decontamination of Equipment

Decontamination of all equipment used throughout aquifer tests conducted at hazardous waste sites is important because contact of contaminated equipment with ground water may compromise the suitability of a well for water quality characterization. Equipment used throughout the duration of an aquifer test should be decontaminated in accordance with the State-approved decontamination and health and safety plans contained in the appropriate field activity workplan(s). All decontamination activities should be described in the site investigation report addressing the aquifer test(s).

5 AQUIFER PUMPING TEST DATA ANALYSIS AND INTERPRETATION

Data analysis and interpretation are the final steps toward achieving the overall objective of conducting aquifer tests: to determine the hydraulic properties of the zones of interest. Accurate analysis of the test data requires a means of recognizing all natural and human-induced factors that impacted the aquifer test and were impacted by it. This recognition should be based on a well-developed understanding of the hydrogeologic setting, the uses and limitations of well hydraulics theory, and the practical aspects of conducting such tests (Driscoll, 1986). Thus, the analysis and interpretation of aquifer test data depend on the following:

- compilation of the data in the form of plots and tables,
- correction of the data for any "external influences" (see Section 4.3),
- calculation of the hydraulic properties of the zone(s) of interest,
- evaluation of the assumptions and limitations of the analytical methods, and
- conceptualization of the hydrogeologic regime and its relationship with the hazardous waste site.

Data collected in the field are unavoidably subjected to a variety of circumstances that may be recognized in the field or may not become apparent until data analysis has begun. In either case, all data collected during the aquifer test--including comments and notes--should again be examined during data compilation and analysis. In so doing, the data analyst should be able to differentiate true aquifer response from mechanical and/or human errors.

5.1 Guidelines for Compilation and Presentation of the Data

Data presentation should clearly identify the methods and rationale used in analysis of the aquifer test data. Additionally, all data necessary to conduct an independent review and analysis should be presented.

5.1.1 Consistency of Units of Measurement

All time data should be converted to a single set of units (minutes), all water level data should be converted to values of drawdown, and all water level and discharge rate data should be expressed in consistent English or metric units.

5.1.2 Presentation of the Data

In addition to the data presentation requirements noted in the previous sections, time, drawdown, and distance information should be presented in the form of graphical plots. These data plots are necessary for any further analysis because calculation of hydraulic properties and characterization of the hydrogeologic regime is most easily interpreted through analysis of the shapes of data arrays on the plots. Whether the data plots are compiled by hand or generated by computer programs, the following guidelines should be met for aquifer test data presentation:

- Data plots of drawdown versus time, depending on the data analysis methods employed, should be presented for the pumping well and each observation well on double-logarithmic and semi-logarithmic paper. Time data (in minutes) should be depicted along the horizontal axis, and drawdown should be depicted along the vertical axis. For semi-logarithmic plots, drawdown should be presented along the vertical arithmetic axis.

- The horizontal scale should be the same for all data plots.

- All data points on the plots should be clearly labeled. In the event that more than one water level measuring device was used for the same well or data from multiple wells are presented on the same plot, the labeling should be distinct so as to enable differentiation between sets of data, and should be identified in a legend.

- Data plots of drawdown versus distance from the pumping well should be presented; calculations of hydraulic properties based on these plots should be used to corroborate calculations made from timedrawdown data plots.

- In the event that drawdown data need adjustment, due to external effects or because of reduction in saturated thickness, separate data plots depicting both adjusted and unadjusted drawdown versus time and versus distance should be presented for the appropriate wells. Any plots, graphs, or equations used to determine the magnitude of drawdown adjustment should also be presented.

- Data plots of residual drawdown versus time since pumping stopped should be presented for recovery data.

- Data plots of discharge rate versus time should be presented.

- All data plots should be included in the site investigation report.

5.1.3 Presentation of the Data Analysis

A number of aquifer test analysis methods are available for various aquifer conditions (for example, Cooper and Jacob, 1946; Neuman, 1972; Theis, 1935). It is beyond the scope of these guidelines to specify how aquifer test data should be analyzed. Rather, the guidelines below indicate minimum requirements for how aquifer test data should be compiled, presented, and summarized.

Data analysis methods should be identified and appropriately referenced in the site investigation report. All assumptions and limitations of the analysis methods should be listed and their applicability to the site discussed in the report. In the event that a computer program is used to perform the analysis, only those software programs that provide analysis of the data based on graphical curve matching, rather than least-squares analysis, and allow for the generation of data plots should be used for computerized aquifer test data analysis. Programs used for analysis should be referenced and all assumptions and limitations should be noted in the report. Equations used for the specific purpose of calculating hydraulic properties should also be included in the report.

For data depicted on double-logarithmic plots, the following requirements should be met:

- If a single type curve has been used to analyze the data, the type curve should be presented directly on the data plot.

- If an analysis method employing a family of type curves has been used, all curves selected to fit the data (including both early and late time responses to pumping, if applicable) should be depicted directly on the data plot, and a discussion addressing the applicability of using multiple type curves should be included in the site investigation report.

- Match point values should be identified on data plots.

For data depicted on semi-logarithmic plots, the following requirement should be met:

- The portion of the data to which a straight line is fit should be indicated on the plot.

In the event that any boundaries are encountered by the cone of depression during the aquifer test, the site investigation report should contain (1) a reference to the data plot on which the boundary's impact can be observed, (2) identification of the type of boundary, and (3) a discussion addressing the boundary's effect on the hydraulics at the hazardous waste site. For pumping wells, an evaluation of casing storage effects should be included.

5.1.4 Presentation of Hydraulic Property Calculation

Accurate calculations of transmissivity, storage coefficients, and hydraulic conductivity are the goal of a properly planned and conducted aquifer test. The guidelines included below indicate the minimum amount of information that should be presented for these calculations.

While calculations of the hydraulic properties can be presented ori the data plots, the resultant values should be presented in tabular format in the site investigation report for all zones monitored during the aquifer test, for both the drawdown and recovery phases, and for all methods used for data analysis. Information presented in tabular format should include the following:

- transmissivity (T), including T_{early} and T_{late}, as well as $T_{average}$, where applicable,

- storage coefficient (S), including S, (specific yield) for unconfined aquifers, S' for confing beds, and S_s (specific storage), where applicable, and

- hydraulic conductivity (K), including K' for confingbeds and $K_{vertical}$, where applicable.

If an analysis method is chosen that allows for the calculation of additional hydraulic properties (such as anisotropy ratios, leakage, or storage in unpumped aquifers), these values should also be included in tabular format in the site investigation report. In the event that hydraulic property calculations are available from other multiple- or single-well aquifer tests conducted at the hazardous waste site, the site investigation report should contain a discussion addressing how the most recent calculations compare with previously obtained values.

5.1.5 Summary of Results

In order to conceptualize how hydraulic properties are related to the overall hydrogeologic regime at a particular hazardous waste site, all site characterization data--including the results of any aquifer tests--should be integrated and -interpreted. Interpretation of the aquifer test data requires that attention be paid to every step of the testing process, and therefore should be substantiated by the appearance of the data plots and the calculations of the hydraulic properties. The following standard represents minimum information necessary for the substantiation of how the aquifer test results are related to the site's hydrogeologic regime.

The site investigation report should include a detailed discussion addressing the following points:

- specification of whether the zone(s) of interest responded to the aquifer test as a confined, unconfined, or semi-confined aquifer system, an aquitard, or a combination of these,
- determination of the probable range of T, K, and S values and their vertical and lateral distribution, and
- identification of remaining data gaps, if any, that need to be addressed with additional aquifer testing or other site characterization work.

6 DESIGN OF SLUG TESTS

Slug tests are conducted by instantaneously introducing into or removing from a well a known volume of water, and then monitoring the return of the water level within the well to its original level. The effects of changing the water level within the well should be transmitted through the well screen and filter pack to the water-bearing zone of interest in a manner that indicates the hydraulic properties of that zone. The resulting rise or fall of water level within the well is recorded and the measurements analyzed by one or more methods.

In addition to bailing out or pouring in a volume of water, the instantaneous water level change can be achieved by other methods. Both the introduction and removal of a solid object of known dimensions, and the change in water level from application of pressure or vacuum, have been used to produce the necessary water level disturbance. With all these methods, the water level disturbance is the result of the addition or removal of a "slug", whether a solid, liquid, or gas.

Properly designed slug tests allow for rapid and economical calculation of the hydraulic conductivity or transmissivity of the zone of interest at a single location. This hydraulic conductivity is representative of only a small volume of the geologic material surrounding the well. Cooper, et al. (1967) determined that the calculation of transmissivity and hydraulic conductivity from slug test data is not particularly sensitive to the technique used for analysis. However, calculation of the storage coefficient of the zone of interest may be reliable only to within an order of magnitude of the true value. It is therefore recommended that storage coefficient values calculated from slug test data be used only as approximate indicators of the storage capability of the zone of interest; more reliable calculations should be obtained from pumping test data.

The guidelines presented below provide an adequate basis for determining point-specific hydraulic properties that will enhance the overall characterization of hazardous waste sites in a rapid, cost-effective manner. Some of the guidelines for pumping tests are equally applicable to slug tests; these cases are identified below.

6.1 Guidelines for the Test Well and Slug

The wells in which slug tests are conducted provide a means of examining the subsurface hydrologic environment. This examination is at a smaller scale than that which occurs with aquifer pumping tests and is representative of a smaller portion of the subsurface. However, the appropriate design and construction of the wells is no less important for slug tests than for the pumping and observation wells used for pumping tests.

6.1.1 "Skin" Effect

Data obtained from slug tests conducted in certain geologic formations may sometimes be difficult to interpret if the well was drilled with a hollow stem auger or drilling fluid containing mud. In such cases, a low-permeability "skin" may line the borehole or enter into the zone of interest, causing the permeability of the geological material near the well bore to be reduced (Faust and Mercer, 1984). Proper well installation techniques and development may reduce such effects of drilling.

Determination of hydraulic properties at hazardous waste sites and/or disposal facilities is important with respect to indicating zones that may serve to isolate or restrict movement of certain contaminants. This determination sometimes occurs by conducting slug tests in wells that were initially installed as water quality monitoring wells. Because these wells are typically not designed for significant ground water extraction, little or no effort may have been expended on well development. Consequently, there may have been no effort made to remove the skin produced by smeared clays along the borehole walls, or drilling mud that may have accumulated on the borehole wall or in the formation itself. Interpretation of slug test data from such a well may inappropriately underestimate the migration potential of contaminants through geologic material and lead to unrealistic and optimistic travel-time calculations (Faust and Mercer, 1984). It is therefore desirable to conduct slug tests in wells that have been properly developed in order to rule out the skin effect in data interpretation.

A discussion describing the development method(s) used at each slug tested well should be included in the site investigation report. For any slug tested well for which the development history is unknown, the site investigation report should contain a discussion addressing the likelihood of skin effects on the slug test data interpretation.

6.1.2 Well Depth

The total depth of the slug-tested well should be established from lithologic information obtained from the following sources:

- geologic cross-sections,
- geologic logs, and
- geophysical logs

This information should be obtained from the installation of a smalldiameter pilot hole, applicable records of nearby wells, and/or from drilling and installation of the slug-tested well itself. Data used to establish the total depth of the well should be included in the site investigation report.

6.1.3 Well Screen Length

Because slug tests impact a particular zone only at the location of the screened interval and filter pack, it is important to know if the well screen fully or partially penetrates the zone of interest. Calculation of hydraulic conductivity for a fully screened zone is simply achieved by dividing the transmissivity by the entire thickness of the zone. However, a partially penetrating well can yield a transmissivity value that is only indicative of that portion of the aquifer or confining bed that is penetrated by the well screen and filter pack. A discussion addressing the length of the screened interval for all wells in which slug tests are conducted at the hazardous waste site should be included in the appropriate site investigation report. Justification for partially penetrating screens should also be provided. In the event that slug tests are conducted in wells with partially penetrating screens, it should be indicated in the site investigation report that the hydraulic property calculations from these wells are only indicative of the screened interval and not of the entire zone of interest.

Screen Slot and Filter Pack Dimensions

Equations used in the analysis of slug test data make use of both the radius of the well and the thickness of the filter pack. The dimensions of the well screen openings, filter pack thickness, filter pack grain size distribution, and filter pack porosity for all wells used for slug tests should be reported in the site investigation report. In the event that the dimensions of the filter pack are not known, justifications for assumptions of these dimensions should be included in the site investigation report. Both the screen slot size and the filter pack material gradation should be designed on the basis of the grain size distribution of the aquifer material (Cal EPA, 1994). The screen slot size and filter pack selection should allow for adequate development of the slug-tested well. Rationale for design and selection of a particular screen slot size and filter pack size should be included in the site investigation report, and should be accompanied by appropriately labeled "as-built" drawings of the slug-tested well.

6.1.5 Selection of the Slug

The addition or removal of a slug of water from wells at hazardous waste sites is not advisable for two reasons: **(1)** the addition of water may preclude the well from being useful for some duration for the collection of ground water quality samples, and (2) the removal of contaminated water from a well requires stringently regulated treatment or disposal. For zones of interest with moderate to high hydraulic conductivities, it is therefore useful to use a solid object to displace a known volume of water. This slug may be composed of any material or materials that are acceptable to introduce into the well. Once this solid slug is applied to the well, the water level in the well can be monitored for its response to the slug.

For zones of interest suspected to have low hydraulic conductivities (such as confining beds), it may be useful to pressurize a packed-off zone in a well and observe the water level response to the application of pressure.

Whenever possible, either a decontaminated solid slug of the appropriate size and composition or pressure delivered to a packed-off zone in the well should be used to conduct slug tests in wells at hazardous waste sites. The following information should be reported in the site investigation report:

- dimensions and weight of the slug,
- composition of the slug,
- manner in which the slug was lowered into and raised from the well,
- whether the slug was fully submerged, or floated in the well,
- nature of the test (i.e., falling and/or rising head test),
- manner in which packers were emplaced and inflated, and
- manner in which pressure was delivered to the packed-off zone.

Although not recommended, if slug tests were conducted with the introduction into or removal of water from a well, it should be reported in the site investigation report. If water has been added to the well, the chemical or stable isotopic analysis results of a representative sample of the added water should be reported, and subsequent ground water quality measurements should be examined to indicate any effects from the introduction of the water. For water removed during the slug test, Section 3.2.7 should be followed.

6.2 Guidelines for Justifying the Number of Slug Tests Conducted

Slug tests allow for the determination of in situ hydraulic properties at a single location. However, properties determined from only a single location are not very useful unless they can be compared with data from other wells and piezometers monitoring the same zone. In order to determine the hydraulic properties of particular zones of interest at hazardous waste sites, several slug tests should be conducted in wells or piezometers in each zone of interest. The site investigation report should contain a map indicating the locations of the wells or piezometers tested, as-built drawings of the wells or piezometers tested, and rationale for the number of slug tests conducted. Multiple slug tests indicate the spatial and statistical distribution of hydraulic conductivity at a hazardous waste site and can thereby indicate heterogeneous conditions that may affect the migration of certain contaminants. When several slug tests are conducted in each zone of interest, the entire range of hydraulic property calculations should be presented in the site investigation report.

7 PERFORMANCE OF SLUG TESTS

As with aquifer pumping tests, slug test results reflect the quality of pre-test planning, well design and construction, and data quality control. The data collection phase of the slug test should indicate if the aquifer response is a result of its actual geologic and hydrogeologic characteristics, or if the response was masked by mechanical aberrations or human activity.

7.1 Guidelines for Water Level Measurements

A complete slug test requires the examination of water level data collected at various times with respect to the application of the slug to the well. For instance, a falling-head test requires collection of pre-test water levels that are then compared with water levels that occur in response to the addition of the slug into the well. A rising-head test requires that water levels be monitored after the slug has been removed from the well, and a recovery to pre-test conditions is approached. When a solid slug is introduced into a well, both falling-head and rising-head tests can be conducted by (a) introducing the slug, (b) monitoring water levels until they have returned to pre-test levels, (c) removing the slug, and (d) once again, monitoring water levels until they have recovered to pre-test conditions.

7.1.1 Water Level Measurements Before Application of the Slug

Neither a falling-head nor a rising-head slug test should be started until the static water level has been established for the zone of interest. The water level representative of the zone to be slug tested should be measured and recorded prior to initiation of the test until the water level stabilizes, but for a period of time at least as long as the expected duration of the slug test. The pre-test water level measurements should be presented in both tabular form and on a data plot in the site investigation report.

Although it is not necessary to monitor pre-test water levels as long as with aquifer pumping tests, it is still necessary to establish a water level baseline against which response to the application of the slug can be measured. In the event that a transducer is used to measure the water level, the slug test should not begin until the water level has equilibrated following the introduction of the transducer.

7.1.2 Water Level Measurements After Application of the Slug

One of the advantages of slug tests is that the tested zones of interest typically respond quickly to the slug (depending on the geologic composition of the zone);. therefore, the tests can be conducted fairly rapidly. Because of the often short test duration, many water level measurements should be taken in a very short time. Consequently, transducers should be used for water level measurements, rather than manually operated measuring devices.

Water levels in lower-permeability zones respond to slug tests more slowly than in high-permeability zones. In such cases, it may be possible to monitor water level changes with manual measuring devices. As with s, accuracy of the measurements should be the prime concern regardless of the measuring device(s) used.

Water level measurements taken during and after application of the slug should be presented in the site investigation report. Presentation of the data should include at least the following information :

- date and time slug test began,
- well and zone tested,
- initial water level before application of the slug,
- water level immediately after the application of the slug,
- time since application of the slug (in appropriate units),
- water levels following application of the slug,
- final stabilized water level, and
- comments noting any unusual events (such as changing weather patterns, or passage of a train or heavy machinery).

The volume of the slug used in the slug test should be compared to the magnitude of the actual water level change in the well to ensure that hydraulic property calculations are based on the impact of the slug on the aquifer. Otherwise, a water level change that is less than what could be attributed to the slug may lead to misinterpretations of the hydraulic properties of the zone of interest. A discussion describing how the water level change in the slug tested well corresponds to water displacement in the zone of interest produced by the slug should be included in the site investigation report. The discussion should also include a description of well dimensions used in hydraulic property calculations. Originals or copies of all field data sheets should be provided in the site investigation report.

7.2 Decontamination of Slug Test Equipment

Statements related to decontamination of equipment used for aquifer pumping tests (Section 4.5) also apply to equipment used for slug tests. Equipment used throughout the duration of a slug test should be decontaminated in accordance with the State-approved decontamination plan contained in the appropriate field activity workplan(s). All decontamination activities should be described in the site investigation report addressing the slug test (s).

8 SLUG TEST DATA ANALYSIS AND INTERPRETATION

A variety of slug test analysis methods are applicable to zones with hydraulic conductivities ranging from high to extremely low values (for example, Bredehoeft and Papadapulos, 1980; Bouwer and Rice, 1976 [and Bouwer, 19891; Hvorslev, 1951). It is beyond the scope of these guidelines to specify how slug test data should be analyzed. Rather, the guidelines indicate minimum requirements for how slug test data should be compiled, presented, and summarized.

8.1 Guidelines for Compilation and Presentation of the Data

8.1.1 Consistency of Units of Measurement

All time data should be converted to a single set of units and all water level data should be expressed in consistent English or metric units.

8.1.2 Presentation of the Data

In addition to the data requirements noted in previous sections, hydraulic head and time information should also be presented on graphical plots. As with multiple-well tests, such depiction of the data is necessary for further analysis because calculation of hydraulic properties is based on the shape of the data plot. The following minimum requirements should be met for slug test data presentation.

- Data plots of change in hydraulic head versus time should be presented for all slug tested wells on **an** arithmetic scale, and either double-logarithmic or semi-logarithmic scale, depending on the analysis technique employed. Time data should be depicted along the horizontal axis, and change in head should be depicted along the verticai axis in all cases.

- All data points on the plots should be clearly labeled and should be identified in a legend. In the event that more than one water level measuring device was used for the same well or data from more than a single slug tested well are presented on the same plot, the labeling should be distinct so asto differentiate between sets of data.

- All data plots should be included in the site investigation report.

8.13 Presentation of Data Analysis

Slug test data analysis methods should be identified and appropriately referenced in the site investigation report. All assumptions and limitations of the analysis methods should be listed and their applicability to the site discussed in the report. In the event that a computer program is used to perform the analysis, only those software programs that provide analysis of the data based on graphical curve matching, rather than least-squares analysis, and allow for the generation of data plots should be used for computerized slug test data analysis. Programs used for analysis should be referenced and all assumptions and limitations should be noted in the report. Equations used for the specific purpose of calculating hydraulic properties should also be included in the report. For analysis methods that employ type curves and the technique of curve matching, the following requirements should be met.

- The portion of data to which type curves are fit should be indicated on the plot.

- If an analysis method employing a family of type curves is used, all curves selected to fit the data should be described in the site investigation report.

For data analysis methods that can be used only if stringent criteria are met, appropriate calculations and a discussion indicating the validity of the method for analysis of the data should be included in the site investigation report.

8.1.4 Presentation of Hydraulic Property Calculation

Accurate and representative calculations of transmissivity and hydraulic conductivity are the goal of a properly planned and conducted slug test. While calculations of the following values can be presented on the data plots, the values themselves should be presented in tabular format in the site investigation report for all wells monitored during all slug tests, for all zones tested, and for each method used for data analysis:

- transmissivity (T),

- hydraulic conductivity (K), including K' for confining beds, where applicable, and

- estimation of storage coefficients for confined aquifers (S) and confining beds (S'), confined and/or S_y (specific yield) for aquifers, where applicable.

In the event that hydraulic property calculations are available from other multiple- or single-well aquifer tests, the site investigation report should contain a discussion addressing how the most recent calculations compare with previously obtained values.

8.1.5 Summary of Results

The following minimum information is necessary to substantiate how the slug tests conducted at the hazardous waste site relate to the characterization of the hydrogeologic regime at the site. The site investigation report should include a detailed discussion addressing the following points:

- determination of the probable range of T and K values (and S values, if applicable),
- determination of how the hydraulic properties affect the movement of contaminants both onsite and offsite (ie., which contaminants can migrate with the ground water, through which zones, and at what velocities),
- comparison of pump and slug test results, if both types of test were performed at the site, and
- identification of remaining data gaps, if any, that need to be addressed with additional aquifer testing or other site characterization work.

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Section:
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